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ADVISORY GROUP ON ELECTRON DEVICES
WORKING GROUP B (MICROELECTRONICS)

SPECIAL TECHNOLOGY AREA REVIEW

ON

SPINTRONICS

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SPECIAL TECHNOLOGY AREA REVIEW ON SPINTRONICS

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DEPARTMENT OF DEFENSE
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SPECIAL TECHNOLOGY AREA REVIEW
ON
SPINTRONICS

EXECUTIVE SUMMARY

The objective of this Advisory Group on Electron Devices (AGED) Working Group B (Microelectronics) Special Technology Area Review (STAR) was to examine the status of spintronics (electronics based on the spin degree of freedom of the electron) as it applies to nonvolatile memories and quantum-based logic and computing. In addition, the information provided at the STAR is expected to be of use to the Services and Department of Defense (DoD) agencies as they formulate an investment strategy for realizing the potential benefits of spin-based technologies for military applications. For example, magnetic tunnel junction (MTJ) based nonvolatile memory has the potential to replace dynamic random access memory (DRAM) and floating-gate nonvolatile memory (Flash). Specifically the objectives of the STAR were to:

- Evaluate the present status and progress in spin-based nonvolatile memory applications.
- Determine the military applications of this disruptive memory technology particularly as it relates applying the technology in space-based applications.
- Review the potential for spin qubit-based quantum logic and computing.
- Identify current technical barriers and impediments; and possible breakthroughs in quantum spin-based computing technologies for future military system applications.
- Develop additional science and technology efforts to expand applications to DoD systems.

The STAR was convened at the Fess Parker's DoubleTree Resort, Santa Barbara, CA on March 19, 2003. A distinguished group of speakers made presentations as follows: from industry on nonvolatile memory technology, from universities on quantum computing and communications and from the Defense Advanced Research Projects Agency (DARPA) on the military applications of spin-based computing. In addition, a university speaker summarized the worldwide efforts in quantum information research. The speakers also participated in two panel discussions that interacted extensively with the AGED Working Group B membership and other attendees at the STAR, answering questions and discussing research needed to expand the military applications of spin-based nonvolatile memories and spin-based quantum computing.

This STAR was held in conjunction with a DARPA workshop on quantum computing and quantum information processing where some of the same presentations were made. This workshop was intended to define the type and scope of future research in this area. Based on this workshop and other workshops conducted this past year, DARPA has continued work in this area.

The following key findings and recommendations emerged from speakers' presentations and subsequent discussions with the AGED Working Group B membership.

Key Findings on Nonvolatile Memory Technology

The development of magnetic nonvolatile memory technologies, especially the MTJ magnetic random access memory (MRAM) is quite advanced. MTJ-MRAM can theoretically be overwhelmingly better than Flash and other nonvolatile memories in terms of system friendliness. Unlike Flash, MTJ-MRAM has unlimited read/write cycles. MTJ-MRAM is currently competitive in terms of power consumption and access performance with other non-volatile memories but MRAM has the highest write speed. Commercial MRAM products are being sampled this year.

Some specific findings are:

- The most advanced industry MRAM efforts are in the MTJ-MRAM area.
- Motorola appears to be closest to commercializing a product - a 4Mb MTJ-MRAM. This memory product utilizes the new Savtchenko switching mode and thus eliminates the half-select problem.
- IBM is developing two potential products in parallel: one classical matrix configuration with a selection transistor for each cell and one cross-point configuration, which does not require the active selection element. The former will have higher performance, the latter promises significantly higher densities.
- NVE is conducting development of magnetic (giant magneto resistive (GMR) and MTJ) sensors with military applications such as unattended sensors for vehicle or troop movement and non-destructive evaluation sensors for faults on airplane wings.

Recommendations for Nonvolatile Memory Technology

In order to achieve the DoD goal of developing nonvolatile memory components that fulfill military application requirements, the following are recommended:

Investment in resolving the problems of the MTJ-MRAM technologies:

(a) The need to develop new write strategies such a spin momentum transfer, which will allow write currents to shrink as manufacturing geometry shrinks. If these efforts are not pursued the consequences may be increasing per bit power consumption with increasing density.

(b) The need to combine a radiation-hard complementary metal oxide semiconductor (CMOS) under layer with the MTJ cell is now being addressed in a licensing arrangement between Honeywell and Motorola. This arrangement and others like it should be encouraged.

(c) The need to continue improvement in high reliability processes and make technology available for trusted military applications.

Investment in the development of other alternative magnetic memory technologies such as the all metal SpinRAM and the technology of spin momentum transfer.

Recent Developments in Nonvolatile Memory Technology Since the STAR

Honeywell and Motorola have a joint development program underway to demonstrate a radiation-hard 1Mb MTJ-MRAM that incorporates Honeywell's radiation hard 0.15micron CMOS silicon-on-insulator (SOI) technology with Motorola's latest MTJ cell. The MTJ layers will be deposited on the CMOS SOI wafer after the third metal level. NVE is developing a magneto-thermal GMR technology that has significantly reduced write current by taking advantage of either Curie or Niel point. In addition, Cypress is planning MRAM product releases (64k and 256k MRAM devices aimed at substituting battery backed-up static random access memory (SRAM)).

Key Findings on Quantum Computing

Quantum computing and quantum information technologies are promising solutions to a number of critical problems of interest to the military and to commercial enterprise. At the time of this review, no implementation technology for a quantum computer has emerged as a clear leader in this technically challenging field. There has, however, been great progress on several key basic components.

Some specific findings are:

- Electrical control of spin coherence has been demonstrated at the basic level. This has been done mainly through the gating of spin-engineered nanostructures.
- Femtosecond operation (control over the setting and changing of quantum mechanical states) has been demonstrated. Quantum repeaters for distributing quantum information have not yet been demonstrated but represent an important technology research area for nearly all of the implementations in the quantum computing or quantum information fields.
- Applications in computing include the factoring of very large numbers, the simulation of large quantum systems, unsorted database searching, complex scheduling, image processing (target recognition) and signal processing.
- Novel DoD applications of quantum information science include optical detector absolute calibration, absolute radiance measurements, single photon sources (and detectors), and enhanced lithographic techniques to reach below the diffraction limit using entangled photons.
- The main challenges facing this technology are decoherence, signal attenuation, limited algorithm development, and scalability.
- A "race" among worldwide efforts is underway. An extensive reporting of the funding and activity in this field (as of January 2003) was presented that shows a strong effort by foreign governments to fund their researchers to compete in this area.

Recommendations for Quantum Computing

The principal recommendation of this STAR is that an enormous effort in basic research is going to be required to realize and implement a quantum computer or information system with real-world applications suitable to a military platform. Continued strong support from the DoD in this area is crucial. The challenges to building a successful system are enormous and will not happen through loose collaborative efforts among academicians applying for a series of small grants.

Strong support of systematic development, such as that suggested by the DARPA FoQuS program, is the way to leverage the efforts to date so that the computing implementations can be explored more fully. A clear message from this STAR was that the rest of the world is not going to stop development of quantum information systems for secure communications and quantum computers and there is a significant risk of the US falling behind.

Recent Developments in Quantum Computing Since the STAR

The DoD has shown a strong interest in the successful demonstration of a quantum computer with the objective to have a systems-engineering approach to building a quantum computer with narrow, targeted goals in the next five to ten years.

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INTRODUCTION

Spintronics (electronics based on the spin degree of freedom of the electron) is of great current interest and has the potential to revolutionize current charge based electronics. For example magnetoresistive (GMR and MTJ)-based nonvolatile memory has the potential to replace Flash and dynamic random access memory (DRAM). It is timely to provide AGED and the Office of the Secretary of Defense with an up-to-date assessment of the military applications in this field.

MAGNETIC NONVOLATILE MEMORIES

The purpose of this section is to provide a summary of the presentations and the discussions held during the STAR about magnetic nonvolatile technologies and their suitability for military applications. It is structured as follows: 1) background on magnetic nonvolatile memory, 2) technology development status, 3) memory requirements for military applications, 4) the extent to which MTJ-MRAM will satisfy these requirements, 5) magnetic memory developments, and 6) future magnetic technology developments,.

Background on Magnetic Memory

Magnetic memories have the potential to become valuable alternative technologies for electronic components. Research to date indicates that electronic memory components based on magnetism have the capability to improve system performance and reduce system costs. In addition, these components are nonvolatile, and their magnetic portions are radiation hard.

Although there are a multitude of magnetic nonvolatile memory approaches, all MRAM devices have a series of common characteristics. All rely on merging two very different technologies: 1) a semiconductor base for an active cell array matrix and ancillary circuitry and 2) a magnetically sensitive storage cell built as a combination of magnetic and semiconductor materials. The storage cell is a multi-layer structure, e.g. magnetic tunnel junction that changes its magnetization state when a certain magnetic field combination is applied to it via currents in neighboring wires. The cell transistor in the array allows selecting the cell for reading. "Bit disturb" defines the phenomenon of corrupting the content of a cell that has been selected non-intentionally along one of the two simultaneously activated half-select current lines that provide the magnetic field for writing.

The major difference between the different types of memories comes from the structure of the storage cell. So far, four different techniques have been employed for storing magnetic information in the cell: 1) AMR (anisotropic magnetoresistance), 2) GMR (giant magnetoresistance), 3) MTJ (magnetic tunnel junction), and 4) CMR (colossal magnetoresistance).

Technology Development Status

For technology reasons (magnetic state discrimination signal too small), AMR based memories have not evolved into the commercial market. GMR based memories have been productized on a very limited basis, but not commercialized. They have a higher discrimination signal than AMR, which allows developing usable memory components. The exploitation of the magnetic tunneling effect has created new perspectives. Unlike GMR, MTJ cells require perpendicularly flowing currents. In addition, they generate a much higher output signal. The former attribute allows building compact cell array matrices, while the latter reduces the complexity of the sensing circuitry. In the last five years, nearly all industry research and productization efforts have been concentrated on MTJ. Finally, an all-metal SpinRAM technology based on the GMR effect is in the basic development stage. Its main promise is a low cost silicon-free technology that is inherently radiation hard.

The specific MRAM efforts discussed at the STAR included (presentation charts are available from the AGED Secretariat):

- Romney Katti, Honeywell, "GMR MRAM with Current-in-Plane Magnetic Devices"
- Saied Tehrani, Motorola, "Tunnel Junction MRAM Technology"
- Jim Daughton, NVE, "GMR Memory and Sensors with Spin-Dependent Tunneling Technology"
- Bill Gallagher, IBM, "Magnetic Tunnel Junction MRAM"
- Richard Spitzer, Integrated Magnetoelectronics (IME), "All-Metal GMR-Based SpinRAM"

Military Application Requirements

Nonvolatile memory components for military missile and space applications require:

- Radiation hardness
- Fast read/write performance
- High density
- Low power
- Long endurance
- Random access capability
- Trusted on-shore fabrication

MTJ-MRAM Suitability for Military Applications

Compared with other memory technologies, MTJ-MRAM has a series of inherent advantages for military applications:

- The magnetic storage cell is radiation hard; however, the semiconductor base is radiation vulnerable. In order to achieve radiation hardness combining the radiation hard magnetic device with a radiation-hard CMOS process is required. Since there is a clear isolation between the CMOS and magnetic components, combining rad hard CMOS with MTJ cells is feasible.
- The density (defined as normalized capacity) of MTJ-MRAM components is determined by the semiconductor technology node. Because every cell needs an active element (transistor or diode) for selection, the cell size can approach $4f^2$. This results in a storage density that is comparable with that of NAND Flash with 1-bit per cell, which is approximately 1.5 Gb/cm^2.
- The power consumption of MTJ-MRAM can be theoretically lower than that of pure semiconductor memories, mainly because of lower leakage and better stand-by currents.
- MTJ-MRAM, like NOR Flash and trapped charge devices, has full random access capability.
- The MTJ-MRAM access performance is generally comparable with that of DRAM and MTJ-MRAM has the fastest write time of all nonvolatile technologies.
- "System friendliness" measures the hidden system costs introduced by a technology. These costs are generated by additional hardware or software that is needed to compensate for the technology limitations, such as asymmetric access, low access performance, limited endurance, or volatility. On a comparative basis, MTJ- MRAM components are much more system friendly than Flash and trapped charge memory components.

In summary: MTJ-MRAM memories can be overwhelmingly better than Flash and other non-volatile memories in terms of system friendliness. Unlike Flash, MTJ-MRAM has unlimited read/write cycles. The MTJ memory cell itself is radiation hard but must be combined with a radiation-hard CMOS process. MTJ-MRAM is at equal terms of power consumption and access performance and MRAM has the highest write speed compared to other nonvolatile memories.

MTJ-MRAM Technology Development Status

- The most advanced industry MRAM efforts are in the MTJ-MRAM area.
- Motorola is closest to commercializing a product. A 4Mb MTJ-MRAM component was described at the 2003 IEDM (Durlam, et al, "A 0.18micron 4Mb Toggle MRAM", 2003 IEDM Technical Digest, paper 34.6). This memory product utilizes the new Savtchenko switching mode and thus eliminates the half-select problem.
- Honeywell and Motorola have a joint development program underway to demonstrate a radiation-hard 1Mb MTJ-MRAM that incorporates Honeywell's radiation hard 0.15micron CMOS/SOI technology with Motorola's latest MTJ toggle cell. The MTJ layers will be deposited on the CMOS SOI wafer after the third metal level.
- IBM is developing two potential products in parallel: one classical matrix configuration with a selection transistor for each cell and one cross-point configuration, which does not require the active selection element. The former will have higher performance, the latter promises significantly higher densities. Both developments appear to be behind schedule, probably because of bit disturb and write current problems. IBM is trying to solve the select problem

by building "twin cells" that use two adjacent cells to store one bit, which doubles the signals and cancels noise, but reduces the density by 50%. It is not known how much time it will take to fix the problems. Also the write current scalability appears to be a fundamental problem.

- NVE is conducting development of magnetic (GMR) sensors with military application such as unattended sensors for vehicle or troop movement and non-destructive evaluation sensors for faults on airplane wings.
- NVE is developing a magneto-thermal GMR technology that has significantly reduced write current by taking advantage of either Curie or Niel point.
- Cypress is still planning MRAM product release (device aimed at substituting battery backed-up SRAM) in collaboration with NVE to sample in late 2004. Cypress has recently released data sheets on two MRAM products (64k and 256k MRAM).

To date, some issues with the MTJ technology have become evident:

- MTJ based cells have open flux structures for which coercivity increases with decreasing cell size, which leads to increased write currents. While Motorola claims to have partially solved the problem through cladding, none of the others have made any progress in this area. The Motorola solution just ameliorates the effect, it does not eliminate it. It also appears that the perpendicular current structure required by the MTJ cell, which is an attractive feature for matrix type structures, does not lend itself to create a totally closed flux cell structure, which prevents write currents from scaling in phase with the manufacturing geometry. Instead, write currents are increasing as geometry shrinks.
- The open flux structure creates the danger to influence adjacent cells. To prevent this, open flux cells have to be wider spaced. As a result, the real cell size is about $20f^2$, approximately 5 times bigger that the theoretical size ($4f^2$), which leads to a similar reduction of the component density. In addition, the overhead circuits in MRAM significantly limit density.
- A further problem appears to be the processing of the very thin films required by the MTJ cell. Motorola and IBM appear to be the most advanced in developing a manufacturing processes that will increase quality and yields. The efficiency of this process is paramount for creating high performance system-on-chip configurations.

Magnetic Memory Technology Development Recommendations

In order to achieve the DoD goal of developing nonvolatile memory components that fulfill military application requirements the following are recommended:

Investment in resolving the problems with the MTJ-MRAM technologies:

(a) The need to develop new write strategies such as spin momentum transfer, which will allow write currents to shrink as manufacturing geometry shrinks. If these efforts are not pursued the consequences may be increasing per bit power consumption with increasing density.

(b) The need to combine radiation-hard CMOS/SOI under layer with the MTJ cell is now being addressed in a licensing arrangement between Honeywell and Motorola. This arrangement and others like it should be encouraged.

(c) The need to continue improvement in high reliability processes and make technology available for trusted military applications. (See IBM white paper entitled "MRAM Development for Space Mission Memory Subsystems" September 2003, available from the AGED Secretariat).

Investment in the development of other alternative magnetic memory technologies such as the all-metal SpinRAM and the technology of spin momentum transfer.

The all-metal SpinRAM is being developed by IME. According to their presentation, in addition to all MTJ-MRAM advantages, SpinRAM offers inherent radiation hardness, the potential for an up to two orders of magnitude increase in density, much above the mechanic-magnetic HDD level, as well as a two orders of magnitude decrease in power consumption. If the technology fulfills the claims IME makes, it appears to be the ideal solution for discrete memory components, embedded memory components and system-on-a-chip solutions. The latter is possible because the technology allows for building not only storage cells based on the spin effect, but also system logic elements like digital logic (the foundation for microcontrollers and microprocessors) and analog circuitry. The potential of the SpinRAM technology should be investigated in detail to assess its potential. (See white paper by J. Spitzer, IME, entitled "Integrated Magnetoelectronics -All-Metal Electronics" April 2003, available from the AGED Secretariat).

Correlation Between Commercial and Military Applications

Military requirements for electronic components in general and for nonvolatile memories in particular are technologically much more demanding than commercial applications. The nonvolatile memory military requirement that is not mandatory for the vast majority of commercial applications is radiation hardness. Even so, military applications will greatly benefit from utilizing technologies with commercial applications, not only because of the larger R&D base, but also because of the quality improvement brought about by the very large manufacturing volumes and the higher technology improvement pace.

Conclusions

The development of magnetic memory technologies, especially MTJ-MRAM, is quite advanced. The first commercial products are being sampled this year. The next step is to create a military-grade component (to be applied to the D5 missile life extension program) by replacing the MTJ-MRAM commercial bulk CMOS base with a radiation-hard CMOS/SOI technology. In addition, the development of methods to reduce the current drive requirements for the MTJ-MRAM technology, such as the magneto-thermal technology, should be continued. The all-metal SpinRAM technology is theoretically capable of producing beneficial nonvolatile memory. There is a value in further investigating this technology.

SPIN-BASED QUANTUM COMPUTING AND INFORMATION SYSTEMS

The purpose of this section is to provide a summary of the presentations and the discussions held during the STAR about spin-based quantum computing technologies and their suitability for military applications. It is structured as follows: 1) background on quantum computing and quantum information, 2) technology development status and recent developments, 3) requirements for military applications, 4) key findings, and 5) recommendations.

Background on Quantum Computing

Quantum computers offer the potential to solve certain classes of computationally intensive problems that would be prohibitively difficult (or impossible) using standard computing methods. These problems include the factorization of large integers, database searching, the simulation of quantum mechanical effects and, more generally, other problems described by partial differential equations. Although there are many candidate approaches to building a quantum computer, the central theme is the entanglement of quantum bits, or qubits. It is useful to begin with a comparison to standard digital computing.

Almost all of today's computers are based on simple Turing Theory and employ Boolean logic based on binary mathematics. Even "parallel" computers are really complex Turing engines employing multiple computing modules, which deal with pieces of incoming data (chunks, bytes, instructions, etc.). There has been some research into biological computing using enzymes or large-molecule systems as memory, shift registers, etc., but this has not proven to be very practical.

Where the digital computer uses binary digits (bits), the quantum computer uses qubits, but qubits are extremely difficult to generate. Quantum computing is based on a different physics than digital computing. Instead of having two states-per-element like digital computers, which are off or on, quantum computers can have all three states at the same time. A classical 8-bit digital computer can exist in only one of 256 states at a time while an eight bit quantum computer can exist in a linear superposition of all 256 states at a time and theoretically, quantum operation works on 256 calculations at once (quantum parallelism). Each of the 256 numbers in this 8-bit example can, if the register is initiated appropriately, have an equal probability of being measured so that a quantum processor can functions as a random number generator. The actual register is representing all of these values at once but a single value output only occurs at measurement. While a classical digital computer would have to operate on each number from 0 to 255, quantum computers require only one pass through the "processor," radically reducing calculation time. Of course, the larger the register size, the larger the number - even a simple 20-bit quantum computer could scream past a supercomputer for an appropriate problem like factoring.

A quantum switch must be undisturbed. The impinging fields required for the proper operation of a quantum computer depend on the interaction of the various qubits without any outside influence. When disturbed, the qubit becomes quite Newtonian rather than quantum and selects a definite state - by chance becoming, dare we say, digital. Paul Benioff of the Argonne National Laboratory first applied quantum theory to computers in 1981 and David Deutsch of Oxford

proposed quantum parallel computers in 1985, years before the realization of qubits in 1995. Qubits are made using various techniques. A group at the National Institute of Standards in Boulder, CO trapped a single atom with missing electrons (an ion) with two energy levels by containing it with magnetic and electric fields at -273 degrees C. Another group at California Institute of Technology made qubits from polarized light using a device, which allows photons to interact while they pass though a stream of cesium atoms interacting in a XOR-like manner. At Los Alamos, researchers make qubits by trapping ions. Ion traps, housing up to six ions, have already been produced - far short of the thousands required for a useable quantum computer.

Although quantum computers at the system level (beyond a few qubits or a gate) have not been built to date, many of the mechanisms required, like error correction and algorithm construction, are being investigated. Because of their multiple states (unlike two-state digital processes) quantum computers will have some of the problems that analog computers had - namely error correction and calculation reliability (although this does not sound very quantum mechanical). Physicists are arguing what type of error correction will work with qubits and quantum measurement in general. John von Neuman's work in computer error detection and correction is being re-examined and has led to new efforts in quantum error correction. The same superposition that gives quantum computation its parallelism may give quantum error correction its power dramatically exceeding classical error correction methods.

For additional background information see Quantum Computation and Quantum Information by M. A. Nielson and I. L. Chuang. Cambridge University Press, September 2000.

Technology Development Status

Quantum computing has been tested or proposed in several physical systems. Here is a brief list of the leading candidates followed by some highlighted examples.

- Liquid State NMR and NMR Spin Lattices
- Linear Ion-Trap Spectroscopy
- Neutral Atom Optical Lattices
- Cavity QED
- Linear Optics with Single Photons
- Nitrogen Vacancies in Diamond
- Electrons in Liquid Helium
- Small Josephson Junctions
- Spin Spectroscopies
- Coupled Quantum Dots

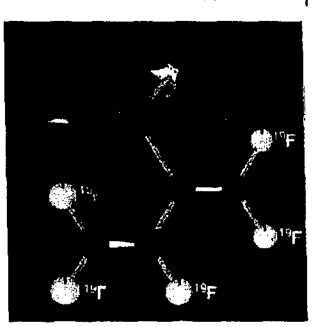
The state of play

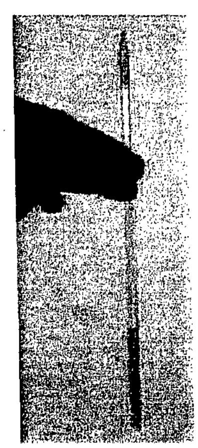
Implementation	qubit	1 qubit operation	2 qubit operation	Max # of qubits
Ion Trap	Ion	YES	YES	10 – 100
NMR	Atom	YES	YES	10 – 100
Linear optics	Photon	YES	??	??
Superconducting	Josephson junction	YES	2003 ?	10^6 ?
Silicon	Atom	2003 ?	2003-2004 ?	10^9 ?

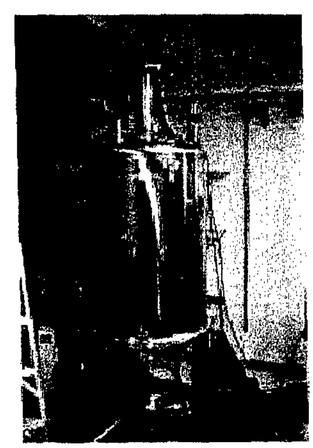
NMR:

Nuclear magnetic resonance (NMR)

- Qubit: nuclear spins of atoms in a designer molecule
- Coupling and single-qubit gates: RF pulses tuned to NMR frequency







Gershenfeld and Chuang, *Science* (1997)

Ion Traps:

Ion traps

- Qubit: internal electronic state of atomic ion in a trap (ground and excited)
- Coupling: use quantised vibrational mode along linear axis (phonons)
- Single qubit gates: using laser

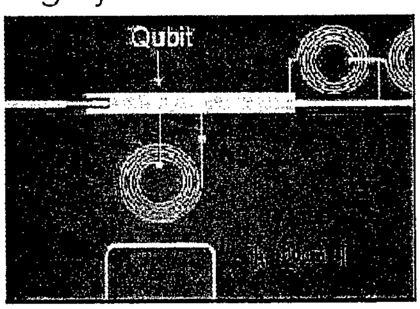
Cirac and Zoller, *Phys. Rev. Lett.* (1995)

Josephson Junctions:

Superconducting Josephson junctions

Qubit: a) Magnetic flux trapped in loop
b) Cooper pair charge on metal box
c) Charge-phase

- Coupling: capacitive/inductive
- Single-qubit gates: flux bias, charge on gate, current through junction

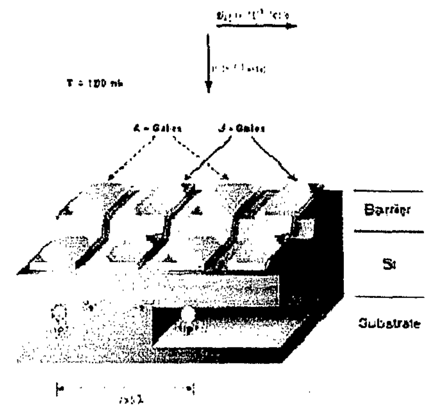


Nakamura, Pashkin, Tsai, *Nature* (1999)

Silicon:

Silicon quantum computing

- Qubit:
  - Nuclear spin of single P donor
  - Electron spin of single donor
  - Electron charge
- Coupling: gate-controlled electron-electron interaction
- Single-qubit gates: NMR pulse; gate bias in magnetic material; charge on gate



QUANTUM COMPUTER Kane, *Nature* (1998)

The specific quantum computing efforts discussed at the STAR included (see presentation charts, available from the AGED Secretariat):

- David Awschalom, UCSB "Spintronics for Logic, Storage, and Computing"
- Eli Yablanovich, UCLA "Quantum Information Processing Using Spins in Semiconductors"
- Stuart Wolf, DARPA "Quantum Information Science and Technology"
- Tatjana Curcic, Booz Allen Hamilton "Quantum Information Science Landscape." An extensive reporting of the funding and activity in this field (this briefing outlines research efforts as of January 2003 and the authors noted that significant changes in the research landscape has occurred during the past year) was presented and is included here at the end of this report in Appendix A. This briefing shows a strong effort by foreign governments to fund their researchers to compete in this area.

Military Application Requirements

Military applications include:

- Factorization (code breaking)
- Searching (pattern recognition, huge database searches, etc)
- Image and signal processing using generalized transforms
- Powerful simulations of large non-linear systems

Key Findings on Quantum Computing and Quantum Information

Quantum computing and quantum information technologies are promising solutions to a number of critical problems of interest to the military and to commercial enterprise. At the time of this review, no single implementation technology for a quantum computer has emerged as a clear leader in this technically challenging field. There has, however, been great progress in several key areas, which has been spurred on in large part by the DARPA QuIST and SpinS programs. A conservative estimate would suggest that fully 80% of the domestic papers authored were reporting work commissioned and supported at least in part by the DARPA QuIST or SpinS programs. The DoD already has a strong interest in the successful demonstration of a quantum computer and this year a new call for proposals for the Focused Quantum Systems DARPA program is planned. The point of the new effort will be to have a systems-engineering approach to building a quantum computer with narrow, targeted goals (in all likelihood a factorization quantum computer) in the next five to ten years.

Some of the specific findings from the presentations at the STAR meeting include:

- Electrical control of spin coherence has been demonstrated at the basic level. This has been done mainly through the gating of spin-engineered nanostructures.
- Femtosecond operations (control over the setting and changing of quantum mechanical states) has been demonstrated. This includes all-optical electron spin resonance techniques for coherent manipulation of the electron spin.
- Ferromagnetic imprinting of nuclear spins has been demonstrated. In hybrid ferromagnetic/semiconductor heterostructures the nuclei in the proximity of a ferromagnetic contact can be manipulated by interacting with the magnetic gate.
- Quantum repeaters for distributing quantum information have not yet been demonstrated but represent an important technology research area for nearly all of the implementations in the quantum computing or information fields.
- Applications in computing include the factoring of very large numbers, the simulation of large quantum systems, unsorted database searching, complex scheduling, and image and signal processing (target recognition).
- Applications in communications include enhanced channel capacity, ultra-precise metrology for geolocation, long-baseline interferometry, and distributed aperture sensing.
- Novel DoD applications of quantum information science include optical detector absolute calibration, absolute radiance measurements, single photon sources (and detectors), and enhanced lithographic techniques to reach below the diffraction limit using entangled photons.
- The main challenges facing this technology are decoherence, signal attenuation, limited algorithm development, and scalability.
- Recent breakthroughs in the implementation of quantum computers have come in the areas of superconducting, semiconductor solid state, ion trap, optical lattice, and nuclear magnetic resonance.
- A "race" among worldwide efforts is underway. An extensive reporting of the funding and activity in this field was presented that shows a strong effort by foreign governments to fund their researchers to compete in this area.

Recommendation on Quantum Computing and Quantum Information

The principal recommendation of this STAR is that an enormous effort in basic research is going to be required to realize and implement a quantum computer or information system with real-world applications suitable to a military platform. Continued strong support from the DoD in this area is crucial. The support of the National Science Foundation for basic research in spintronics and quantum computing should be encouraged. Without previous DoD funding, the great body of work leading to recent breakthroughs would not have happened and would not be ongoing. The challenges to building a successful system are enormous and will not happen through loose collaborative efforts among academicians applying for a series of small grants. Strong support of systematic development, such as that suggested by the DARPA FoQuS program, is the clear way to leverage the efforts to date so that the implementations can be explored more fully. A clear message from this STAR was that the rest of the world is not going to stop development of quantum information systems for secure communications and quantum computers and there is a significant risk of the US falling behind.

APPENDIX A
Tatjana Curcic and Stuart Wolf "Quantum Information Science Landscape"

Quantum Information Science Landscape

Stu Wolf

University of Virginia

Tatjana Curcic, Julia Vollmers

Booz Allen Hamilton

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Q-Communications and Cryptography: *Experiment and Theory*

	North America	Europe	Asia, Oceania, Russia
Quantum Communication	APL/JHU BBN Caltech IBM LANL MagiQ MIT MITRE NIST Stanford Telcordia UCLA UCSB	Geneva Id Quantique Innsbruck Orsay Vienna LMU	Mitsubishi NEC Tokyo Tamagawa
Q-Comm and Cryptography Theory	AT&T IBM LANL Montreal UNM	Bristol Cambridge Erlangen LMU Oxford	Hong Kong Japan Korea

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QC Implementations: *Experiment and Theory*

	North America	Europe	Asia, Oceania, Russia
NMR	MIT, Harvard, IBM, LANL, Stanford		NIMS, RIKEN
Ion Trap	NIST, LANL, Michigan	Innsbruck, LMU, Oxford, MPQ	
Neutral Atoms	NIST, Arizona, UNM, Caltech, GaTech, Harvard, UCB	MPQ, Orsay, ENS, Aarhaus, Innsbruck	
Optical	APL/JHU, UIUC, LANL, BU, JPL, UCSB, UMBC, Toronto, TAMU	RAMBOQ, Rome, Geneva, Bristol, Oxford, Vienna, Imperial	Queensland, Macquarie, China
Solid State	Harvard, NRL, Michigan, UCSB, UMD, Pittsburgh, Ottawa, Michigan, UIUC, Wisconsin, UCLA, IBM, NCSU, Stanford, UCSD, TAMU, LANL	Delft, Basel, Torino, Wuerzburg	USNW, Melbourne, Tokyo
Super-Conducting	MIT, SUNY SB, Kansas, IBM, NIST, JPL, UMD, TRW, Yale, LL, Rochester, LPS	Delft, Saclay, Pisa, Erlangen, Karlsruhe	NEC, RIKEN, NTT
Architecture	MIT / UCD, NIST		

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Theory

	North America	Europe	Asia, Oceania, Russia
Q-Algorithms	AT&T, MIT, UCB, Columbia, HP, Lucent, Caltech	Oxford, Cambridge, Amsterdam	Kyoto
QEC / Fault Tolerance	Caltech, Toronto, Microsoft, MIT, UCB, AT&T, LANL, Waterloo	Oxford, Torino, LMU	
Q-Complexity	UCB, IBM, Montreal, Calgary, Caltech, Microsoft	Amsterdam	
Q-Information Theory	IBM, LANL, Williams, AT&T	Bangor, Poland, Imperial, MPQ, Bristol, Nottingham	Queensland, Moscow, Nagoya
Q-Control	SCS, Princeton, MIT, Caltech	Oxford, Cambridge	

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Major Strengths

North America

- *NMR* (MIT, Harvard, IBM)
- *Semiconductor Solid State* (UCSB, Harvard, UCLA, NRL)
- *Ion Trap* (NIST)
- *Quantum Optics* (LANL/UIUC, BU, UMBC, TAMU)
- *Theory*
  - ***QEC/FT*** (Caltech, Toronto, Microsoft, MIT, UCB)
  - ***Q-Algorithms*** (Caltech, MIT, UCB)
  - ***Q-Information*** (IBM)
  - ***Q-Comm & -Crypto*** (IBM)
  - ***Q-Control*** (Caltech, Princeton, MIT)

Australia

- *Quantum Optics* (Queensland)
- *Solid State* (CQCT)

Europe

- *Q-Communication* (Geneva)
- *Neutral Atoms* (MPQ, ENS)
- *Ion Trap* (Innsbruck, MPQ)
- *Quantum Optics* (Bristol, HP Euro Lab, Vienna, Geneva)
- *Superconducting QC* (Delft, Saclay)
- *Theory*
  - ***Q-Information*** (Imperial Coll., Bangor, Poland, MPQ)
  - ***Q-Comm & -Crypto*** (Cambridge, Bristol, Oxford)
  - ***Q-Algorithms*** (Amsterdam, Oxford, Cambridge)
  - ***QEC*** (Oxford)

Japan

- *Superconducting QC* (NEC, RIKEN)
- *Q-Communication* (NEC, Mitsubishi))

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Recent Breakthroughs: *Implementations*

Superconducting QC

- Entanglement of two charge qubits observed (*RIKEN/NEC*).
- Many Rabi oscillations observed in phase (*Kansas*), charge-phase (*Saclay*), and flux (*Delft*) qubits, with decoherence times in μs.

Semiconductor Solid State

- Entanglement observed in quantum dots(*NRL/Wuerzburg, NRL/Michigan*).
- Single-spin control (*Delft*) and single-spin measurement (*Harvard*) demonstrated in quantum dots.
- Electrical control of spin coherence (*UCSB*).
- Spin lifetime of 60 ms demonstrated in Si at 7K (*Princeton*).

Ion Trap

- First q-algorithm (Deutch-Jozsa) demonstrated in an ion trap (*Innsbruck*).

Optical Lattice

- Mott-insulator transition demonstrated for loading optical lattice (*MPQ, NIST*).
- Conditional two-atom phase shifts in state-dependent lattice demonstrated (*MPQ).*

NMR

- Shor's algorithm demonstrated to factor 15 (*IBM*).

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Recent Breakthroughs: *Theory, Q-Communication*

Quantum Algorithms

- Exponential speed-up with a quantum algorithm for Pell's equation (*Caltech*).
- Adiabatic quantum algorithms (*MIT*).
- Quantum algorithm for solving a class of PDEs faster than classical (*Columbia*).

QC with Linear Optics

- Theoretical proposal for universal QC with linear optics (*LANL/Queensland*).

Quantum Communication

- Long distance teleportation of qubits at telecommunication wavelengths (*Geneva*).
- 87 km quantum cryptosystem at telecommunication wavelengths (*Mitsubishi*).

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QC Funding – Europe , United States

Funding Agency	Title	Description	Amount	Years
Europe: FP5	Quantum Information Processing and Communication (QIPC)	12 projects: QIPC falls under FET (Future Emerging Technologies). Interdisciplinary, with areas in nuclear physics, computer science, semiconductor engineering, quantum optics and mathematics	22M Euro	1999-2002
Europe: FP6	QIPC	Will fall under third call of FET proactive scheme in FP6, 2004		2002-2005
USA: DARPA	QuIST, SPINS	25 projects in Q-communication and Q-computation		
USA : ARDA	Quantum Information Science	Solid-State Approaches, Non-Solid-State Approaches, Quantum Information Theory. Has BAA out	$20-30M	2001-
USA: NSF	QuBIC – Quantum and Biologically Inspired Computing	Only ~5 of 17 projects are of interest to quantum (i.e., not biology)	~$5M total; individuals $400-500k	2003-2006
	ITR (small, medium and large)	California Institute of Technology: Institute for Quantum Information	$5M	2000-2005
		University of Wisconsin Madison: Quantum Information Processing with Two-Dimensional Atomic Arrays	$2M	2002-2007
		Case Western Reserve: Quantum Computing Using Electrons on Helium Films	$2.5M	2000-2005
		University of California Berkeley: Exploration and Control of Condensed Matter Qubits	$4.5M	2002-2007
		Other ITR	$4.5M (all ~$500k)	3 years ending 03 or 04

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QC Funding - Australia

Funding Agency	Centre	Details	Funding	Duration
Australian Research Council (ARC)	Centre for Quantum Computer Technology	Established in 2000 by ARC. One of eight Centers around Australia	Initial Injection of A$9M, Operating fund of A$30M over 4 years	2000-2003
	Center of Excellence in Quantum Computer Technology	Continuation of above. One of eight Centers of Excellence in Australia. Sharing A$90M for the five-year period. QCT collaborating with ten other universities and research laboratories in Australia and the US	A$14M (~$8.5M USD)	2003-2007

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QC Funding: Japan

Japanese S&T (JST)

Ministry	Project	Years	Funding	Researchers
Ministry of Public Management, Home Affaire, Posts and Telecommunication	Quantum Cryptography	2001-2005	3.01 Oku JPY in 2003	TAO of Japan:outsources to Mitsubishi Electrical Co Ltd, NEC Inc, and Tokyo University
Ministry of Education, Culture, Sports, Science and Technology	Quantum Information Manipulation	2003-2010	160 Oku JPY for 8 years	Stanford, and JST to outsource as ERATO Projects

JST Funding Programs in QIS

- Core Research for Evolutional Science and Technology (**CREST**)
- Exploratory Research for Advanced Technology (**ERATO**)
- International Cooperative Research Project (**ICORP**)

120 JPY = $1
1 Oku = 10^8 JPY≅ $0.83M

Data from Asian Technology Information Program (ATIP)

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QIS Japan Funding: Large Projects

- **CREST** (Core Research Evolutionary Science and Technology)
  - Functional Evolution of Materials and Devices based on Electron/Photon Related Phenomena (1999-2004): $1M / year / group, 3 QIS groups
    - QIS groups: Tokyo Inst. Tech. (coherent q-dynamics in SS devices), Osaka Univ. (nuclear spin network QC), NEC (cryptography)
- **ERATO** (Exploratory Research for Advanced Technology):
  - Quantum Computation and Information Project, started 2000: $15M / 5 years
    - Univ. of Tokyo, Kyoto Univ., NEC
  - Tarucha Mesoscopic Correlation Project, 1999-2004
- **ICORP** (International Cooperative Research Project)
  - Quantum Entanglement: 1999-2004 $10M / 5 years: Stanford/NTT (Y. Yamamoto) and ENS (S. Haroche)
    - Crystal Lattice Quantum Computation, semiconductor cavity QED, entangled electrons, photons and single spin measurements
    - Quantum Measurement Theory

Data from Asian Technology Information Program (ATIP)

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QC Funding – Korea, China, Taiwan

Funding Agency	Title	Description	Amount	Years
Korea: Ministry of Education	Brain Korea 21 Program	Quantum Information Science	$450k	3 years
Korea: Ministry of Science and Technology	Quantum Information Processing and Systems	University of Seoul, Solid State QC	$1M / year	1998-2007
	NMR based Quantum Computation	At KAIST supported National Research Laboratory	$750k	5 years
Chinese Academic Sinica	Quantum Physics and Information Program		4M RMB / year ~$480k / year ($100~830RMB)	1999-?
China: National Natural Science Foundation of China	Information Science Division	Received a Proposal on QIT – Not yet decided		
China: Ministry of Science and Technology	Key Laboratory of Quantum Information at University of Science and Technology of China	Major areas: Q-Cryptography, Q-Communication, Q-Computation, Q-Fundamental Theory		
China: Ministry of Education	Key Laboratory of Quantum Information at Tsinghua University			
Taiwan: NNI		Evaluating a joint QIS proposal by research from National Cheng Kung University and Institue of Physics, Academia, Sinica. Area of Q-Computation Algorithms	Possible $500k	TBD

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APPENDIX B
Terms of Reference

DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES (AGED)
WORKING GROUP B (Microelectronics)

SPECIAL TECHNOLOGY AREA REVIEW
ON
SPINTRONICS

<u>TERMS OF REFERENCE</u>

STAR ORGANIZERS:
Les Palkuti, DTRA
Stuart Wolf, DARPA

LENGTH: 1 day including discussion

VENUE: Fess Parker's DoubleTree Resort, Santa Barbara, CA

TIME: 19 March 2003

WHY TOPIC IS APPROPRIATE FOR AN AGED STAR:
Spintronics (electronics based on the spin degree of freedom of the electron) is of great current interest and has the potential to revolutionize current charge based electronics. For example, giant magnetoresistive (GMR)-based non-volatile memory has the potential to replace Flash and DRAM. It is timely now to provide AGED and OSD with an up to date assessment of the military applications in this field.

OBJECTIVES:
1. Evaluate the present status and progress in spin-based nonvolatile memory applications.
2. Determine the military applications of this disruptive memory technology particularly as it relates applying the technology in space-based applications
3. Review the potential for magnetic quantum-based logic and computing.
4. Identify current technical barriers and impediments; and possible breakthroughs in quantum spin-based computing technologies for future military system applications.
5. Develop additional science and technology efforts to expand applications to DoD systems.

BACKGROUND:

Until very recently, the spin of the electron was ignored in mainstream charge-based electronics. A new electronics technology based on the spin transport of the electron or spintronics has recently emerged, where it is not the electron charge but the electron spin that carries information. Spin-based electronics offers remarkable opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects that arise from the interactions between electron spin, magnetic field and the magnetic properties of the material. An important spintronic device is the non-volatile memory based on the giant magnetoresistive effect. Within the next two years several companies including Motorola and IBM will introduce these magnetic non-volatile random access memories using the magnetic tunnel junction devices. This memory has significant military potential by replacing much of the existing semiconductor memories including Flash and DRAM and embedded GMR devices form the memory elements in robust system-on-a-chip technology. Recent discoveries about induced spin coherence and spin injection into semiconductors have opened up even more possibilities for revolutionary devices that can supplement or even supplant charge based semiconductor electronics for logic operations. The prospects of developing a whole new computing infrastructure based on the quantum mechanical nature of electron or nuclear spin have emerged in recent years and there are several large efforts that are trying to fabricate and understand the properties and limitation of spin based quantum bits. (For additional background see S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. Daughton, S. von Molnar, M. Roukes, A. Y. Chtchelkanova, D. M. Treger, Science, Vol 294, Nov 2001, pp 1488-1495; or Zorpette, Glenn, "The Quest for the Spin Transistor", IEEE Spectrum, Dec 2001, pp 30-35 - articles attached)

STAR OVERVIEW:

Nonvolatile Memory

These applications talks will provide in depth reviews of the major efforts to develop magnetic random access memory (MRAM) based the magnetic tunnel junction devices integrated with CMOS. The first MRAM products are expected within the next two years. In addition, a magnetic Schottky tunnel contact device and process will be explored that has the potential for a 100-fold increase in memory density.

Spin-Based Quantum Computing

The next series of talks will focus on the development of a host of new technologies that rely on the controllable interactions of coherent spins with ferromagnetic materials to produce quantum logic operations. Recent advances in spin transport, spin injection and coherent spin behavior have enhanced the prospects for novel new devices for logic that may be faster and lower power than just charge based electronics. These talks will describe how spin is the perfect quantum bit or qubit that will make it possible for quantum computation. DoD applications for this technology will be addressed in detail.

Agenda

- GMR MRAM with Current-in-Plane Magnetic Devices, Romney Katti, Honeywell
- Tunnel Junction MRAM, Speaker Saied Tehrani, Motorola
- GMR Sensors with Spin-Dependent Tunneling Technology, Jim Daughton, NVE
- Magnetic Tunnel Junction MRAM, Jim Gallagher, IBM

- Panel Discussion - Research needs to expand military applications of spin-based memory and sensors
- Spintronics for Logic, Storage and Computing, David Awschalom, UCSB
- Communication and Cryptography Based on Quantum Repeater Device, Eli Yablonowitch, UCLA
- Possible Military Applications for Spin-Based Computing, Stuart Wolf, DARPA
- Panel Discussion - Research needs to expand military applications of spin-based computing

QUESTIONS TO BE ADDRESSED BY STAR:

1. What are the DoD systems and applications that will benefit from giant-magnetoresistive, non-volatile memory technology? What are the prospects for early insertion of tunnel junction technologies and the Schottky tunnel-contact device?
2. What are the commercial requirements for embedded, magnetic non-volatile memory? What DoD applications (such as radiation hard system-on-a-chip) can be accelerated by leveraging commercial investments?
3. What are the technical barriers to be overcome that limit the application of spin coherence spin injection into semiconductors and spin-based devices for logic functions and ultimately to quantum-based computing? Can these barriers be prioritized with respect to return on investment?
4. What is the impact of ongoing DoD S&T investment in spin-based devices and quantum computing, relative to the needs of DoD and the three Services, the needs of the US industrial base, and the needs of university research programs? What additional S&T effort and funding is needed?
5. What is the proper mix of basic (6.1) and development research (6.2 and 6.3) efforts? What is the appropriate mix of S&T efforts to extend current technology as opposed to introducing new device concepts, device development, performance modeling and simulation, etc?

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APPENDIX C
Agenda

DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES (AGED)
WORKING GROUP B (MICROELECTRONICS)

SPECIAL TECHNOLOGY AREA REVIEW
on
SPINTRONICS

Wednesday, March 19, 2003

0730-0830	Continental Breakfast and Registration	
0830-0840	Introduction	
0840-0920	GMR MRAM with Current-in-Plane Magnetic Devices	Romney Katti, Honeywell
0920-1000	Tunnel Junction MRAM	Saied Tehrani, Motorola
1000-1040	GMR Memory and Sensors with Spin-Dependent Tunneling Technology	Jim Daughton, NVE
1040-1100	*Break*	
1100-1130	Magnetic Tunnel Junction MRAM	Bill Gallagher, IBM
1130-1200	SpinRAM – All metal, based on GMR	Richard Spitzer, IME (Integrated Magnetoelectronics)
1200-1230	Research needs to expand military applications of spin-based memory and sensors	Panel Discussion
1230-1330	Lunch	
1330-1420	Spintronics for Logic, Storage and Computing	David Awschalom, UCSB
1420-1510	Communication and Cryptography Based on Quantum Repeater Device	Eli Yablonovitch, UCLA
1510-1545	Break	
1545-1635	Possible Military Applications for Spin-Based Computing	Stuart Wolf, UVA
1635-1650	Quantum Information Science Landscape	Tatjana Curcic, UVA
1650-1715	Research Needs to Expand Military Applications of Spin-Based Computing	Panel Discussion
Meeting Adjourns		

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ACRONYMS

AGED	Advisory Group on Electron Devices
AMR	Anisotropic Magnetoresistance
CMOS	Complementary Metal Oxide Semiconductor
CMR	Colossal Magnetoresistance
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DRAM	Dynamic Random Access Memory
GMR	Giant Magneto Resistive
MTJ	Magnetic Tunnel Junction
MRAM	Magnetic Random Access Memory
S&T	Science and Technology
SOI	Silicon on Insulator
SRAM	Static Random Access Memory
STAR	Special Technology Area Review
S&T	Science and Technology